Heterogeneously integrated III-V/Si multi-wavelength laser based on a ring resonator array multiplexer

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Abstract: A 4-channel multi-wavelength laser integrated on a silicon waveguide circuit is realized. Waveguide-coupled output powers of 2mW and a side mode suppression ratio of more than 45dB for all channels is realized.

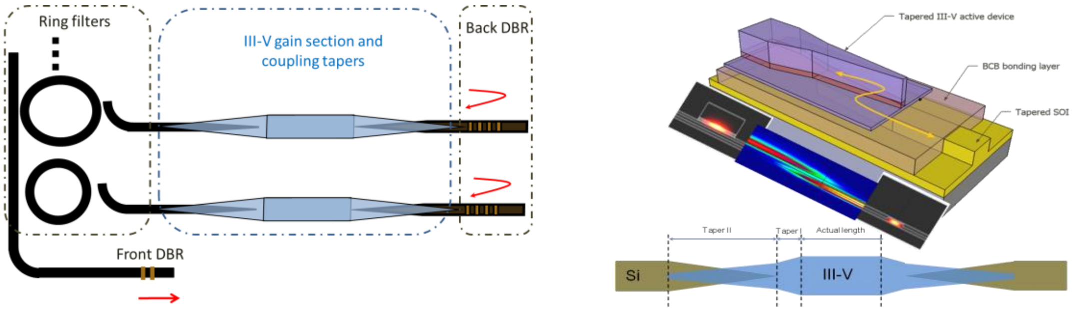
OCIS codes: (250.0250) Integrated optics; (250.5300) Photonic integrated circuits; (250.5960) Semiconductor lasers.

1. Introduction

Silicon-On-Insulator (SOI) waveguide circuits are widely studied because of the large refractive index contrast that is available on this platform, which allows realizing ultra-compact devices. The interest in this technology stems also from the expectation that the maturity and low-cost of CMOS-technology can be applied for advanced photonic products [1]. Since silicon lacks efficient light emission and amplification, the integration of III-V semiconductors on top of silicon waveguide circuits is required to achieve complex integrated circuits. Several approaches can be followed to realize this integration. Heterogeneous integration through die-to-wafer bonding and direct hetero-epitaxy allow for dense and wafer-scale integration of the III-V opto-electronic components on the silicon photonic platform. Since the quality of hetero-epitaxially grown layers is inferior to III-V epitaxy grown on its native substrate, the heterogeneous integration of III-V semiconductors on silicon using a wafer bonding technique is currently the most relevant solution for the fabrication of laser sources on silicon. In order to densely integrate the III–V semiconductor with the silicon waveguide circuits, mainly molecular wafer bonding and DVS-BCB adhesive bonding techniques are used and are actively reported in state-of-the-art hybrid amplifiers [2-3] and lasers [4-6]. In these approaches, unstructured InP-based dies are bonded, epitaxial layers down, on an SOI waveguide circuit wafer, after which the InP growth substrate is removed and the III–V epitaxial film is processed. In this paper we show that using a DVS-BCB adhesive bonding process compact heterogeneously integrated III-V/silicon multi-wavelength lasers can be realized, which are key optical components for wavelength division multiplexed optical networks and optical interconnects.

2. Device design

In order to realize a III-V/silicon multi-wavelength laser an intracavity wavelength (de)multiplexer is required, which can be implemented in different ways. Classically an arrayed waveguide grating (AWG) is implemented [7]. In this paper we implement a ring-resonator based (de)multiplexer, as shown in Figure 1(a). This offers some distinct advantages over an AWG: the ring resonator resonance wavelengths, defining the emission wavelengths of the different laser channels can be individually thermally tuned to provide an arbitrary and versatile channel spacing. Secondly, the ring resonator structure is more compact that AWGs, definitely when a small channel spacing is required. This wavelength (de)multiplexer is implemented in silicon photonics, using a 220 nm thick silicon guiding layer on a 2 μm buried oxide layer. The III-V thin film optical amplifier is implemented as a 3 μm wide mesa etched through to the n-type InP contact layer. In this particular device implementation the amplifier section was 500 μm long. The III-V layer stack consists of a p-InGaAs contact layer, a p-InP cladding layer (1.5 μm thick), six InGaAsP quantum wells (6 nm) surrounded by two InGaAsP separate confinement heterostructure layers (100 nm thick, bandgap wavelength 1.17 μm) and a 200 nm thick n-type InP layer. The optical coupling between the III-V amplifier waveguide and the silicon waveguide circuit is realized using an adiabatic spot size converter by tapering down the III-V waveguide width to below 500 nm and also implementing a taper in the silicon waveguide layer. In order to provide efficient optical coupling, the silicon taper is implemented in a 400 nm thick silicon rib waveguide structure



(a) (b)

Figure 1: (a) Device layout of the realized III-V/silicon multi-wavelength laser; (b) sketch of the adiabatic spot-size converter used for optical coupling between the III-V amplifier waveguide and silicon waveguide layer.

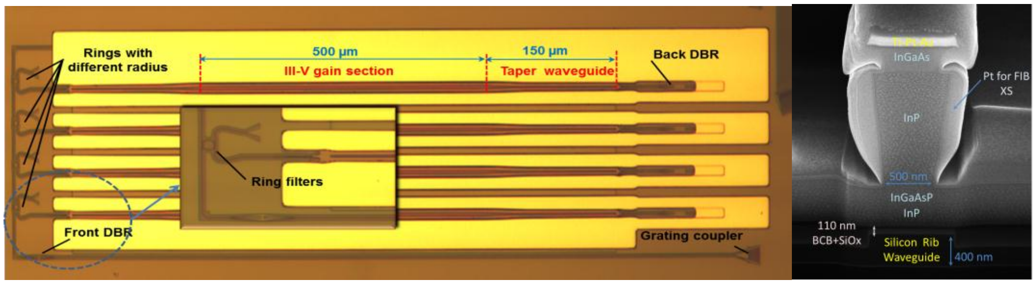
(etched 180 nm), which is then in its turn efficiently coupled to the 220 nm device layer using a short adiabatic taper structure. The III-V/silicon taper structure, shown in Figure 1(b) consists of two sections: first, the III-V mesa is tapered from 3 µm to 900 nm over a length of 45 µm after which the III-V mesa is gradually tapered from 900 nm to 500 nm over a length of 150 µm. The silicon waveguide underneath tapers from 300 nm to 1 µm over 150 µm. The DVS-BCB bonding layer thickness, determining the separation between the silicon waveguide layer and the III-V layer is 110 nm in this implementation. The silicon (de)multiplexer circuit consists of 4 ring resonators coupled to the same bus waveguide. The free spectral range of the ring resonators is 15.5 nm and the loaded quality factor of the resonators is larger than 3000, providing sufficient suppression of longitudinal laser cavity modes adjacent to the lasing longitudinal mode (longitudinal mode spacing of 250 pm in this device implementation). The reflectors are implemented as distributed Bragg reflectors etched on the surface on the silicon waveguide layer, using a 290 nm grating period, 70 nm etch depth and 50% duty cycle. The high reflectivity mirror consists of 40 grating periods (resulting in a reflectivity > 90% and a 3dB bandwidth of 100 nm), while the partially reflecting mirror consists of 8 periods, resulting in 45 % maximum reflection and a 3dB bandwidth of 140 nm. For the interfacing to optical fiber, diffractive grating couplers structures are used, using the same 70 nm etch depth in the 220 nm device layer, but using a second order grating design (grating period 625 nm, 10 degree fiber angle).

3. Device fabrication

The fabrication process starts with the processing of the SOI wafer incorporating a 400 nm thick silicon waveguide layer in a CMOS pilot line. The first etch step comprises the definition of the 400 nm rib waveguides by etching 180 nm deep in the silicon waveguide layer. This at the same time also creates the 220 nm device layer for the implementation of the passive silicon circuitry. Next, the first order Bragg reflectors and second order fiber grating couplers are defined using a 70 nm etch step, while in a last step the 220 nm strip waveguide structures are defined. 193 nm deep UV lithography is used on 200mm SOI wafers to define these waveguide structures. An SiO_2 cladding layer is deposited and the wafer is planarized using chemical mechanical polishing (CMP). Next, the III-V epitaxial layer structure grown on its InP substrate is bonded upside down onto the silicon device layer, using a 110 nm thick DVS-BCB bonding layer. The details of this bonding process can be found in [8]. After bonding, the InP substrate is removed by wet chemical etching until an InGaAs etch stop layer is reached. This results in a III-V epitaxial layer stack attached to the silicon waveguide circuit, which can then be processed, lithographically aligned to the underlying SOI waveguide circuit. A Ti/Pt/Au stripe, acting as a p-side contact and also as a hard mask for the mesa etching was defined with a lift-off process using 320 nm UV contact lithography. Selectively wet etching was used to etch through the InGaAs layer, the InP p-doped layer and the MQW. Due to selected correct crystal orientation, a negative sidewall slope can be achieved in the anisotropic etching of InP. GeAu/Ni was used for the n-contacts. The active waveguide is encapsulated with DVS-BCB and extra Ti/Au contacts layers were added for the contact pads. Figure 2(a) shows a microscope image of the fabricated device, before p-type metallization. The III-V amplifier waveguides and the ring resonator (de)multiplexer array can clearly be identified. The footprint of the multi-wavelength laser structure is 1100 µm by 300 µm. Figure 2(b) shows a scanning electron microscope picture of the III-V taper tip fabricated using wet chemical etching as explained above.

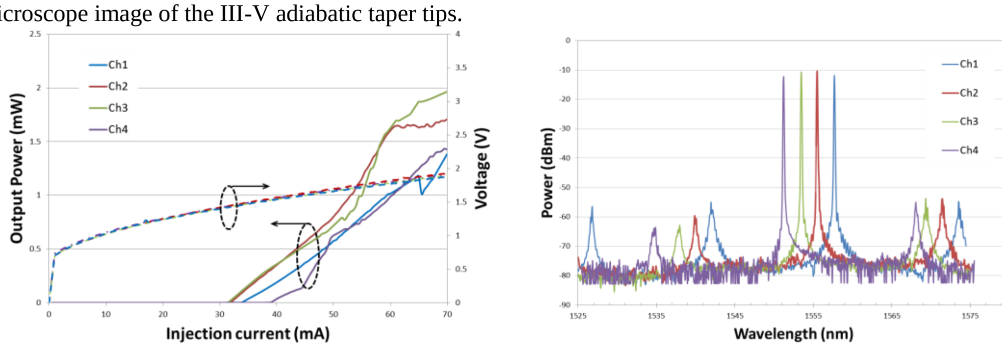
4. Device characterization

The fabricated multi-wavelength laser is characterized on a temperature controlled stage at 20°C. The output power in the silicon waveguide versus drive current of the optical amplifiers is shown in figure 3(a), showing a threshold current of 31 mA, 31 mA, 33 mA and 39 mA for the four respective channels. The slope efficiency in the different



(a) (b)

Figure 2: (a) microscope image of the fabricated multi-wavelength laser indicating the various subcomponents ; (b) scanning electron microscope image of the III-V adiabatic taper tips.



(a) (b)

Figure 3: (a) waveguide-coupled optical output power versus amplifier drive current for the four different channels; (b) superimposed spectra of the four laser channels

channels varies between 30 mW/A and 37.5 mW/A. A waveguide-coupled output power between 1 and 2 mW is obtained. These levels of optical output power and electrical power consumption are compatible with practical applications. Figure 3(b) shows the lasing spectra of the four channels superimposed. A side mode suppression ratio better than 45 dB is obtained on all four channels.

5. Conclusion

In this paper we demonstrate the use of III-V on silicon heterogeneous integration to realize a multi-wavelength laser source with mW-level optical output powers and good spectral characteristics. Since the output light is coupled to a silicon waveguide, a next step is to externally modulate the multi-wavelength continuous wave signal using low power consumption silicon ring resonator modulators [9]. This way low power consumption wavelength division multiplexed transmitters can be envisioned based on this III-V on silicon waveguide platform. Recently, we demonstrated the co-integration of III-V-on-silicon lasers with silicon high-speed electro-optic modulators [10].

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